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Verification Times Underlying the Kyoto Protocol: Consideration of Risk

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IIASA Interim Report
December 2002

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Interim Report **IR-02-066**

Verification Times Underlying the Kyoto Protocol: Consideration of Risk

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Approved by

Sten Nilsson
Deputy Director and Leader, Forestry Project

July 2003

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Abstract

This paper proposes a probabilistic (risk-based) approach to address verification of changes in global net carbon emissions — here, the change in atmospheric CO_2 and CO_2 emissions from fossil fuel combustion, cement production and gas flaring, under the Kyoto Protocol. A methodology is developed that permits assessing these net emission changes, which are characterized by uncertainty distributions, in terms of their verification times. The verification time is the time until a net emission signal begins to outstrip its underlying uncertainty. For a number of reasons, namely (1) data availability, (2) consistency in accounting net carbon fluxes, and (3) spatio-temporal conditions, which correspond to the current level of sophistication that is realized in the approach, it is applied to the global scale. However, the temporal verification conditions of the approach correspond to those on sub-global scales, in accordance with the Protocol. Two conclusions emerge from this study: (1) characterizing changes in global net carbon emissions by equal-sided (symmetric) uncertainties, as practised by the Intergovernmental Panel on Climate Change, leaves valuable information unutilized; and (2) the comparison of probabilistically and deterministically determined verification times shows that they differ — the probabilistic verification time tends to be greater (more conservative) compared with the deterministic verification time.

Acknowledgments

I would like to express my thanks to those who made my participation in the Young Scientists Summer Program (YSSP) of 2002 possible: to the Forestry Project team, to all IIASA staff, and the 2002 YSSP participants. In particular, I am grateful to Yuri Ermoliev and Matthias Jonas for their helpful guidance. I also very much appreciate Shari Jandl's assistance in editing this paper.

My appreciation goes to the Swedish NMO — The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) for their generous financial support.

About the Author

Halyna Hudz is a research scientist at the State Scientific and Research Institute of Information Infrastructure in Lviv, Ukraine. During the summer of 2002, she was a participant in IIASA's Young Scientists Summer Program (YSSP) affiliated with the Forestry (FOR) Project. Her research related to the investigations of uncertainty, verification, and risk management under the Kyoto Protocol.

Verification Times Underlying the Kyoto Protocol: Consideration of Risk

Halyna Hudz

1 Introduction

1.1 Background

This paper deals with the issue of uncertainty, verification, and risk management under the Kyoto Protocol, which is being studied at IIASA by the Forestry (FOR) Project in collaboration with the Risk, Modeling and Society (RMS) Project. This work is a continuation of research started by the author under the guidance of Y. Ermoliev and M. Jonas, funded by the Austrian Federal Ministry of Education, Science and Culture. Previous results were presented at the Workshop *Greenhouse Gas Accounting: Uncertainty – Risk – Verification* that was held at IIASA on 13–14 May 2002 as well as at the First International Conference on Inductive Modeling Methods held in Lviv, Ukraine on 20–25 May 2002.

1.2 Initial Expectations

In 1999, IIASA initiated research on the topic of uncertainty and verification in the context of the Kyoto Protocol. The Forestry (FOR) Project developed a deterministic approach, called the verification time concept (VTC), which is proposed to calculate verification times (VTs) underlying the Kyoto Protocol. The relevance and needs of a risk-based VTC approach are investigated. Our initial expectations were that the probabilistic approach of the VTC may help to assess data more correctly, particularly in terms of their uncertainties, and may also (significantly?) affect derived VTs in comparison with VTs determined deterministically.

1.3 Objectives

According to our initial expectations, research focuses on the following tasks:

- *Studying the conditions under which it is possible to use the probabilistic VTC approach:* To assess initial data characterizing the changes of net carbon fluxes; to analyze this data in terms of uncertainties; and to describe the uncertainties from a probabilistic point of view.
- *Developing a methodology for setting the VTC on a probabilistic basis:* To formulate the problem and to develop the methodology.

- *Applying the probabilistically based VTC and analyzing its strengths and weaknesses:* To apply the probabilistic VTC methodology; to analyze the results; and to compare the results with data obtained in the deterministic case.

This paper presents the results of my scientific work. In Section 2, I introduce the need and relevance of considering the VTC and the main aspects of the known approaches in general. In Section 3, I analyze changes in global net carbon emissions — here, atmospheric CO_2 and CO_2 emissions from fossil fuel combustion, cement production and gas flaring — in terms of their uncertainties, and in Section 4 I develop a methodology for the probabilistic estimation and projection of VTs, based on the probabilistic description of uncertainties. I apply the probabilistic VTC on the global scale. The results of this work are presented and discussed in Section 5, and Section 6 summarizes my study in the concluding remarks.

2 Overview

2.1 Kyoto Protocol: Objectives and Obligations

At its third meeting in Kyoto in 1997, the Conference of the Parties (COP) adopted the Kyoto Protocol (UNFCCC, 1999) to the United Nations Framework Convention on Climate Change (FCCC) (UNFCCC, 1992), under which nations have to assess their contributions to sources and sinks of greenhouse gases (GHG) and to evaluate the processes that control GHG accumulation in the atmosphere.

The Kyoto Protocol sets quantitative limits on the emissions of six GHGs or groups of gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6). For Annex I Parties, the targets agreed upon under the Protocol by the first commitment period (2008–2012) add up to a decrease in GHG emissions of 5.2% below 1990 levels in terms of CO_2 equivalents. Non-Annex I Parties are not required to take on specific commitments for emission reductions. In addition, the Protocol endorses emissions trading (ET, Article 17), joint fulfillment and implementation (JI) between Annex I Parties (Articles 4 and 6), and a clean development mechanism (CDM, Article 12) that allows Annex I and non-Annex I Parties to act together to reduce emissions (FCCC, 1998; see also Jonas *et al.*, 1999b; Jonas and Nilsson, 2001).

The rules for entry into force of the Kyoto Protocol require 55 Parties to the Convention to ratify (or approve, accept, or accede to) the Protocol, including Annex I Parties accounting for 55% of that group's CO_2 emissions in 1990 (FCCC, 1998). With the European Union's (EU) delivery of its ratification documents to the United Nations in New York on 31 May 2002, the first criterion for the Protocol to become international law — ratification by a minimum of 55 Parties — is achieved. To overcome the second threshold — ratification by the industrialized world's CO_2 emissions in 1990 — now hinges on ratification by Russia, although the United States (the world's biggest polluter representing about a quarter of 1990's emissions) and Australia have rejected Kyoto. However, Russia's Cabinet approved ratification in April 2003, thus adding the crucial share to enable the Protocol to enter into force (CAN Europe, 2002; Claussen, 2002a, b; FCCC, 2002; IISD, 2002).

2.2 Need and Relevance of the VTC

Many problems exist that are related to the implementation of the Kyoto Protocol. As mentioned in Section 2.1, each country needs to develop under the Protocol a national inventory system to assess its net GHG emissions. These emissions must be reported in the form of annual inventories by using approved guidelines and compliance with targets, deviations from which will be assessed at the end of the first commitment period (2008–2012). Penalties for failing to comply include tougher targets in the second commitment period. To help parties and legal entities (i.e., individual companies and corporations) achieve these targets, they can utilize several "flexibility mechanisms", which allow, among other things, trade in emissions and sharing of burdens amongst parties. National bodies, legal entities, and projects will be required to report GHG emissions and carbon sequestration. Projects have to be validated to ensure that they comply with the rules of the trading mechanisms, and inventories have to be "verified" (by independent entities) to ensure that the correct assessments have been accurately applied.

The first question Kyoto countries will face at the end of the commitment period will be: Did they fulfill their duties? And the next question will be: How did they do this? This is because, according to the obligations under the Protocol, a country has to acquire emission reductions (i.e., traded units) if it did not manage to reduce its emissions as agreed. Or the other way around: if a country fulfilled its duties and saved more emissions than agreed, it will be possible for the country to trade these emissions. Therefore, in each of the two cases the correct assessments of the countries' emissions are necessary because these assessments will amount to money.

Practice shows, however, that very often it is difficult to determine which party has met its Kyoto target "better" and which Kyoto party is more credible, especially when it comes to emissions trading (see Figure 1). This example demonstrates that not only correct assessments of emissions are necessary, but also correct assessments of their uncertainties.

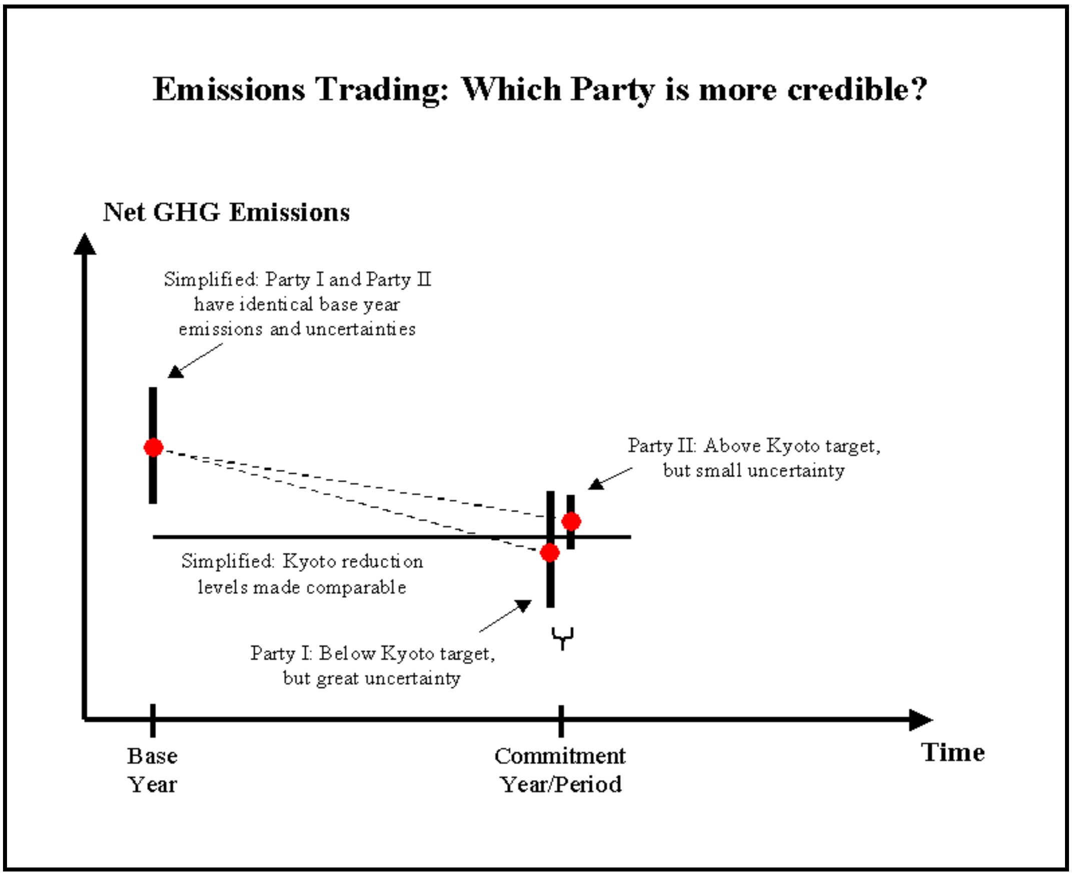

Figure 1: Simplified graphical representation to illustrate the importance of uncertainty and verification in the context of the Kyoto Protocol — here, addressing the crucial question of credibility. The uncertainty intervals of both Party I and Party II encompass the same Kyoto target, but which Party is more credible for ET? Party I reveals a greater uncertainty interval, the mean of which undershoots the Kyoto target, while Party II reveals a smaller uncertainty interval, the mean of which, however, does not comply with the Kyoto target (IIASA, 2002).

As can be seen from this example, the issue of implementing the Kyoto Protocol is also related to the issue of evaluating uncertainties. Several ways exist to graphically visualize the need of introducing and evaluating uncertainties for the verification of GHG emissions. Figure 1 motivates this need from a credibility viewpoint, while Figure 2 directs attention to the scientific shortcomings of insufficient temporal verification.

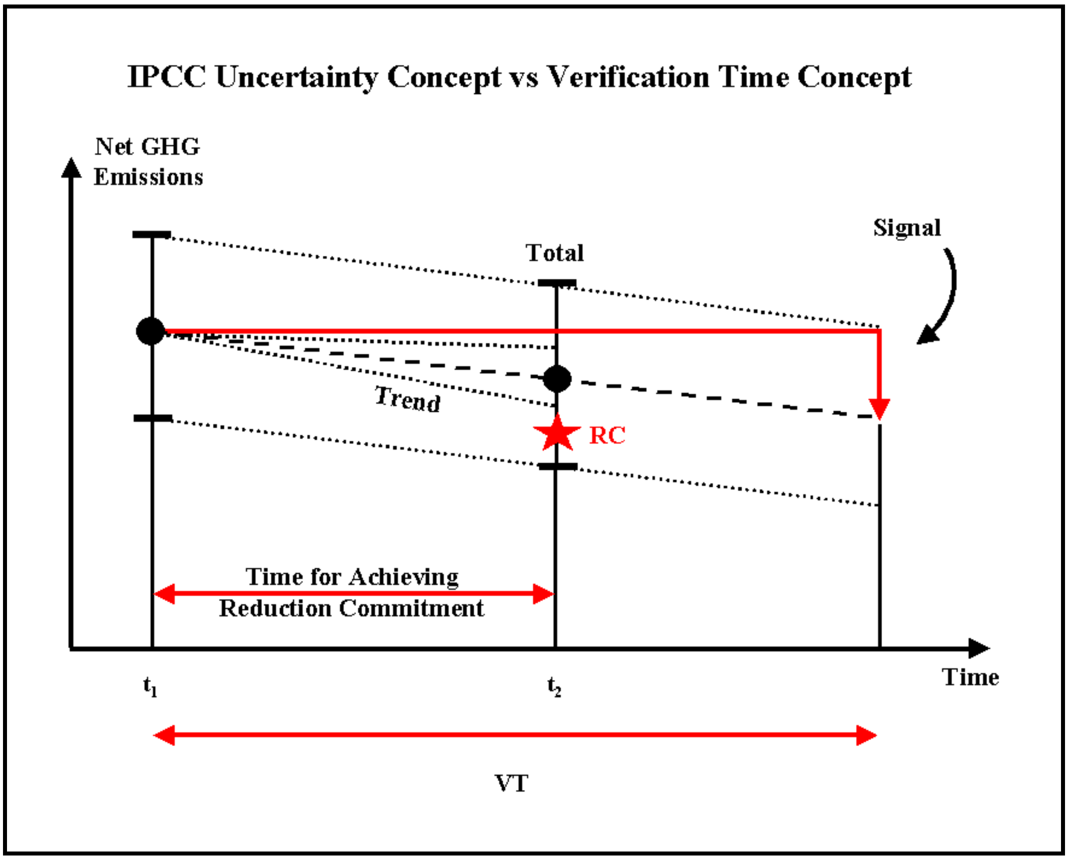

Figure 2: Simplified (linear) graphical representation to contrast the shortcomings of insufficient temporal verification. The figure shows: (1) the two-points-in-time uncertainty concept (here: with respect to t_1, t_2), i.e., the two uncertainties, which are currently discussed in accounting carbon under the Kyoto Protocol (IPCC, 2000a, b): level (or total) uncertainty and trend uncertainty; and (2) a dynamical verification concept, termed VTC, which takes the past (here: linear) dynamics of a country's emission signal into consideration to decide whether or not the net emissions of the country differ detectably from its committed Reduction Target (RC) (Jonas *et al.*, 1999b, 2000; Jonas and Nilsson, 2001). In this example, the VT — the time until the emission signal begins to outstrip its underlying uncertainty — is greater than the time for achieving the reduction commitment (t_2-t_1), confirming: (1) that the realized emission reduction is not verifiable at all at the time point of commitment (the emission signal has not yet outstripped level uncertainty), and (2) that the interpretation of the country's realized emission reduction in terms of the two-points-in-time (total or trend) uncertainty concept must be rejected (IIASA, 2002).

It becomes clear that verification must be the center of the implementation procedure of the Kyoto Protocol. Verification is an issue that requires scientific clarification and it will be up to the scientists to ultimately decide whether or not the net emissions reported by a country are verifiable. This may involve far-reaching, unintended political and/or economic consequences for the Protocol. The details of the VTC as well as an overview of known VTC approaches are described in Section 2.3.

2.3 Addressing Verification

Scientists strictly distinguish between plausibility, validation, and verification. The definition of verification used here as a reference is taken from the Intergovernmental Panel on Climate Change (IPCC, 2000a: Annex 3). It is sufficient as it specifies verification towards the intended purpose of the Kyoto Protocol, which can only be done from an atmospheric point of view: What matters is what the atmosphere sees![1]

This requires consistent Full Carbon Accounting (FCA) on the spatial scale of countries, i.e., the measurement of all fluxes, including those into and out of the atmosphere (as observed on earth), but also atmospheric storage measurements (as observed in the atmosphere), which would — to reflect the needs of the Kyoto Protocol — permit discriminating a country's *Kyoto biosphere* from its *non-Kyoto biosphere*. This type of FCA would permit verification, which is ideal because it works bottom up–top down (*two-sided* or *dual-constrained* verification). However, it is unattainable as there is no atmospheric measurement available (and will also not be available in the immediate future), which can satisfy this requirement (Jonas *et al.*, 2000; Jonas and Nilsson, 2001: Section 3.1.2; see also, e.g., Steffen *et al.*, 1998; Jonas *et al.*, 1999a; Nilsson *et al.*, 2000a, b, 2001, 2002; Orthofer *et al.*, 2000).

Global carbon research addresses verification, but as of today, verification priorities of global carbon research differ from those under the Kyoto Protocol. This research focuses primarily on the global and sub-global (regional) quantification of carbon sources and sinks and their combination in a closed budget, as well as understanding how the budget changes with time as a function of natural and anthropogenic perturbations. A number of measurements, including those of carbon isotopes and atmospheric oxygen as well as eddy covariance measurements, are combined for ferreting out the different fluxes that result from the use of fossil fuels or are exchanged between land or ocean and the atmosphere (e.g., Heimann, 1996; IPCC, 1996: Chapter 2; IGBP, 1997; Heimann *et al.*, 1999; Battle *et al.*, 2000; Falkowski *et al.*, 2000; Pedersen, 2000; Canadell and Noble, 2001). In principle, this community chases the footsteps of bottom up–top down verification on global and sub-global scales.

By way of contrast, the Kyoto Protocol requires that net emissions of specified GHG sources and sinks, including those of the *Kyoto biosphere* but excluding those of the *non-Kyoto biosphere*, be verified on the spatial scale of countries by the time of commitment, relative to the emissions in a specified base year (FCCC, 1998, 2001a, b; WBGU, 1998; IPCC, 2000a, b; Jonas *et al.*, 2000; Jonas and Nilsson, 2001). The relevant question is then whether these changes outstrip uncertainty and can be verified — temporally.

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[1] IPCC (2000a: Annex 3): ***"Verification refers to the collection of activities and procedures that can be followed during the planning and development, or after completion of an inventory that can help to establish its reliability for the intended applications of that inventory.*** *Typically, methods external to the inventory are used to check the truth of the inventory, including comparisons with estimates made by other bodies or with emission and uptake measurements determined from atmospheric concentrations or concentration gradients of these gases".*

However, although this viewpoint is very critical as to how the global carbon research community can contribute specifically to the issue of country-scale verification under the Kyoto Protocol, there is not the slightest doubt about the future need of their guiding work on global and sub-global scales and relation to other Kyoto relevant issues (see, e.g., Steffen *et al.*, 1998; Schulze *et al.*, 2000; IGBP, 2001).

Only recently, more and more attention is being given to solving the problem of temporal verification (Anderson, 2001, 2002; Smith, 2001; Tenner, 2000, 2002). Different institutions and organizations around the world have understood its importance and now deal with this research question. Table 1 lists the approaches and concepts to verify net GHG emissions under the Kyoto Protocol.

Table 1: Overview of the various approaches that are currently elaborated in Austria (IIASA), Poland (SRI/PAS[2]), and Ukraine (SSRIII[3]) to better distinguish dynamical systems (here: net CO_2 emitting systems) from one another. The relevant differences between the major characteristics of the various approaches are underlined. Source: Modified from IIASA (2002).

Approach	**Major Characteristics**	**References**
Deterministic (dynamic moments up to the second order)	Capable of distinguishing systems with <u>different</u> dynamical characteristics from one another (e.g., energy systems and terrestrial biosphere). In these cases, the systems' dynamics eclipse the systems' uncertainties in terms of importance.	Jonas *et al.* (1999b), Jonas and Nilsson (2001), Gusti and Jęda (2002)
Integral transforms	Ongoing research with the objective of distinguishing systems with <u>similar</u> dynamical characteristics from one another: The <u>full-scale</u> characterization of signal dynamics appears promising.	Dachuk (2002)
Statistical	Ongoing research with the objective of initially distinguishing <u>energy</u> systems with <u>similar</u> dynamical characteristics from one another: The characterization of signal dynamics appears promising to be expanded <u>to systems revealing dynamical characteristics other than exponential growth</u>. The involved <u>statistically based</u> smoothing of data results in a reduction of uncertainty, the distribution of which is used to express the VT <u>statistically</u>.	A publication by Nahorski, Jęda and Jonas, which follows up on Gusti and Jęda (2002), is under development

[2] System Research Institute, Polish Academy of Sciences.
[3] State Scientific and Research Institute of Information Infrastructure.

2.4 Main Aspects of the Deterministic Approach

The main aspects of the deterministic approach of the VTC were formulated by Jonas *et al.* (1999b). Their condition for verification requires that the absolute change in net carbon emissions (emission signal), $\left|\Delta F_{net}(t_2)\right|$ at time t_2, with reference to time t_1 ($t_1 < t_2$), is greater than the uncertainty in the reported net carbon emissions at time t_2, $\varepsilon(t_2)$. This condition permits favorable verification:

$$\left|\Delta F_{net}(t_2)\right| > \frac{\varepsilon(t_2)}{2}\ , \tag{2.1}$$

or, under the non-restrictive assumption that first-order (i.e., linear) approximations are applicable:

$$\left|\frac{dF_{net}}{dt}\right|_{t_1} \Delta t > \frac{\varepsilon(t_2)}{2}. \tag{2.2}$$

This concept is visualized in Figure 3, where F_{net} describes the net carbon emissions and $\pm\frac{\varepsilon}{2}$ (defined via F^{+} and F^{-}, the upper and lower uncertainty limits of the net carbon emissions) the uncertainty in F_{net}; Δt is called the verification time for the dynamical system considered under Equations (2.1) and (2.2).

If Equation (2.2) is considered for the case $\left|\frac{dF_{net}}{dt}\right|_{t_1} > \frac{1}{2}\left(\frac{d\varepsilon}{dt}\right)_{t_1}$, the verification time is given by the inequality

$$\Delta t > \frac{\varepsilon(t_1)}{2\left|\frac{dF_{net}}{dt}\right|_{t_1} - \left(\frac{d\varepsilon}{dt}\right)_{t_1}}\ . \tag{2.3}$$

It should be noted that in this — deterministic — approach it is assumed that uncertainty can be represented by equal-sized intervals. But when we have additional information about uncertainty, e.g., when the uncertainty can be characterized by a probability distribution, we can and may even need to make use of a probabilistically based verification time concept. In the remainder of the paper, the probabilistic approach is developed, applied and investigated in terms of its consequences.

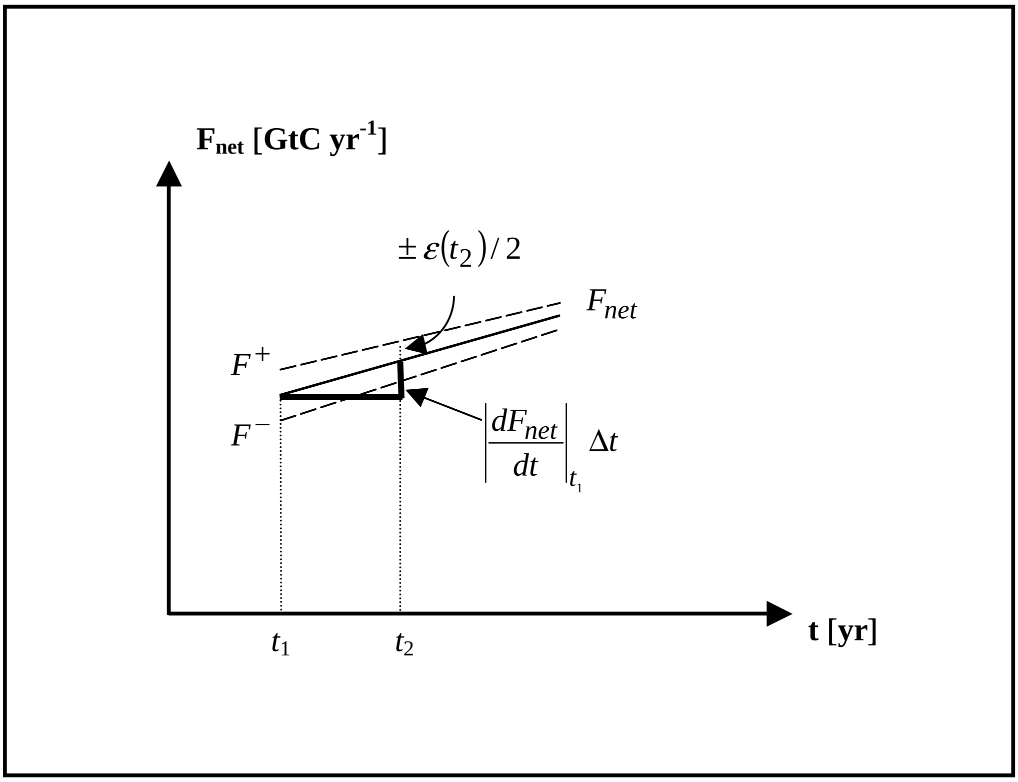

Figure 3: Favorable verification: Simplified linear graphical representation of Equation (2.2) for increasing net carbon emissions (F_{net}) and a decrease in their uncertainty ($\pm\frac{\varepsilon}{2}$). Source: Jonas *et al.* (1999b).

2.5 Perspectives of the Probabilistic Approach

Let us consider the case when uncertainty is represented by a probability distribution (see Figure 4). We can now think of many scenarios (straight lines *A*, *B*,…) instead of only one average scenario (straight line *F*) assuming trends are linear. Each of the scenarios *A*, *B*, … is consistent with the given uncertainty intervals or their underlying probability distributions, respectively. Hence, it becomes apparent that for trend *A* the verification time is greater than for *F*, but for trend *B* the verification time is shorter. We note that scenarios *A* and *B* represent only two possibilities out of the many probable ones that we can consider. It therefore becomes evident that we can assess the VT also in a probabilistic fashion, which essentially depends on the probability distribution underlying the uncertainties, and on how the signal changes (here, as mentioned before, assuming linear trends).

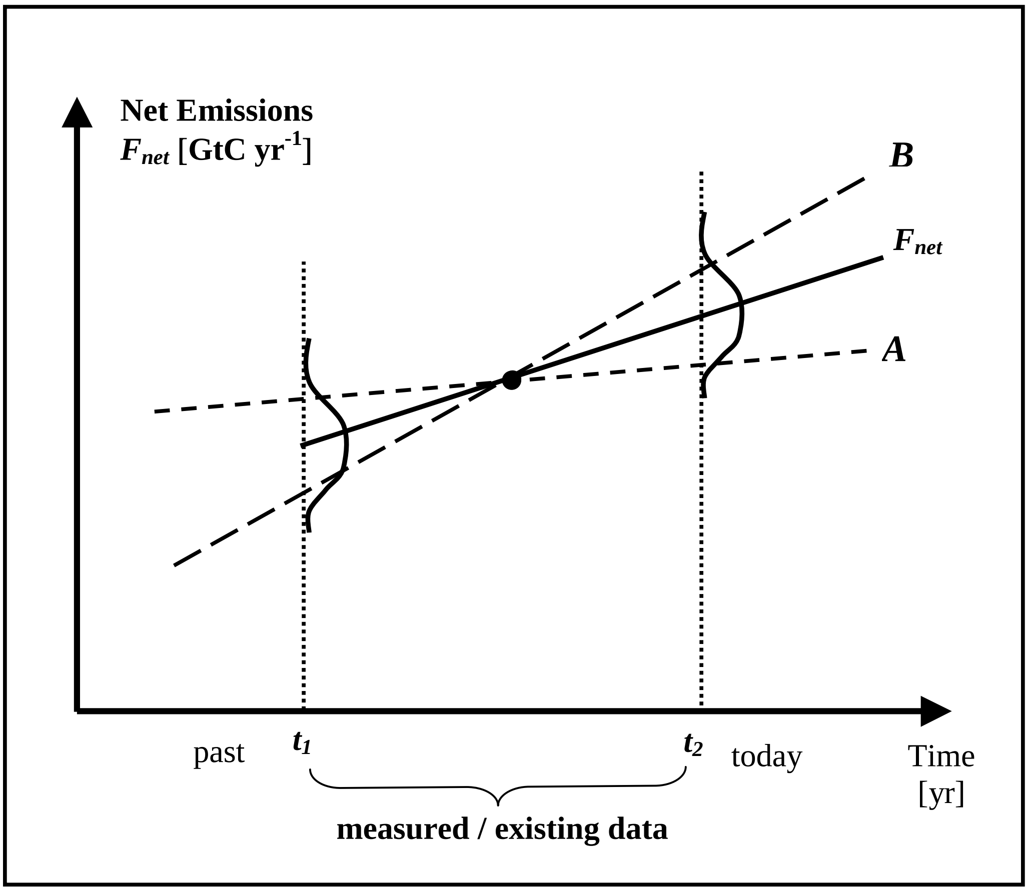

Figure 4: Simplified illustration of the probabilistic approach, for which it is assumed that net carbon emissions (F_{net}) change linearly: A and B are two possible realizations of F_{net} (which is also used here to indicate the mean trend); they are consistent with the uncertainty probability distributions of F_{net} at t_1 and t_2. However, the VTs for A and B are different: For A it is greater than for F_{net}, while for B it is smaller than for F_{net}. F^+ and F^- serve as linear boundary conditions for the uncertainty intervals at t_1 and t_2.

The probabilistic approach requires knowledge on the distributions of net carbon fluxes. In the next Section we analyze net carbon fluxes and their uncertainties on the basis of real data. We will show, that:

- these distributions may be different from normal, and
- the description of uncertainty by symmetric intervals around the mean value can be misleading.

3 Data Analyses

3.1 Assumptions and Applied Conditions

We examined and analyzed net carbon fluxes on the global scale. For reasons of

- data availability,
- consistency in accounting net carbon fluxes, and
- spatio-temporal conditions, which correspond to the current level of sophistication that is realized in the approach,

investigations are carried out on the global scale (where decadally resolved signal changes can be considered to be sufficiently linear). The key idea underlying these calculations is that temporal verification conditions on sub-global scales are simulated [see also Section 3.1.2.5 in Jonas and Nilsson (2001)]. To these ends, we considered the classical IPCC representation of global net carbon fluxes as shown in Figure 5. We used the available data and sources reported by the IPCC (1990; 1995; 1996; 2000a, b; 2001). Some of this data could be used in the initial form, but other data had to be processed prior to further use.

According to the IPCC, the atmospheric carbon budget is composed of anthropogenic emissions, exchanges between the ocean and the atmosphere, exchanges between the terrestrial biosphere and the atmosphere and the atmospheric increase (see Figure 5) (IPCC, 1990; 1995; 1996; 2000a, b; 2001).

Classical Approach for Calculating Carbon Budget Changes

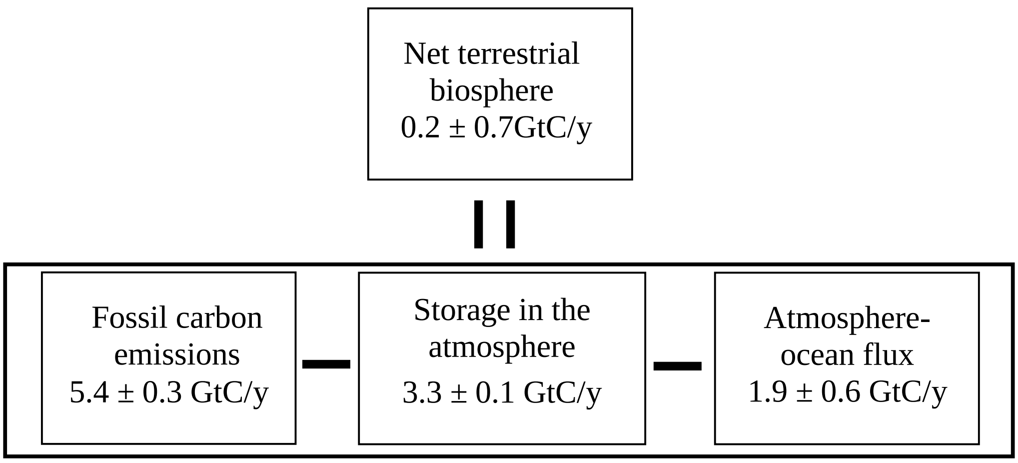

Figure 5: Global budget of CO_2 perturbations for 1980 to 1989 based on data from the IPCC (2001).

Several approaches are used by the IPCC to quantify the components of the carbon budget, often in combination:

- Direct determination of the rates of changes of the carbon content in atmospheric, oceanic, and terrestrial carbon pools, either by observations of inventory changes or by flux measurements.
- Indirect assessment of the atmosphere-ocean and atmosphere-terrestrial biosphere fluxes by means of carbon cycle model simulations either calibrated or partially validated using analogue tracers of CO_2, such as radio-carbon or tritium, or using chlorofluorocarbons.
- Interpretation of tracers or other substances that are coupled with the carbon cycle.

We will show that, as a result of the various measurements, net carbon fluxes are represented by functions with a very different and non-homogeneous structure, which is influenced by seasonal, annual as well as decadal variations. In Sections 3.2–3.4, we will also show that these functions of net carbon fluxes may not be evenly distributed around their mean values. As a consequence, the use of mean values with equal lower and upper uncertainty limits may only serve as a first approximation, or may even become questionable in the presence of multi-modal distributions.

3.2 Carbon Measurements in the Atmosphere

In this Section, we consider the observed changes of the atmospheric carbon budget. The time period 1980–1989 was chosen for data availability reasons.

Precise and direct measurements of atmospheric CO_2 commenced at the South Pole and Mauna Loa, Hawaii in 1957. Data from the Mauna Loa station are close to, but not the same as, the global mean. Atmospheric concentrations of CO_2 have been monitored for shorter periods at a large number of atmospheric stations around the world (Boden *et al.*, 1991). Measurement sites are distributed globally and include sites in Antarctica, Australia, Asia, Europe, and North America. The global average of CO_2 concentration, as determined through the analyses of NOAA/CMDL[4] data (IPCC, 1995, 2001; Boden *et al.*, 1991; Conway *et al*., 1994; Globalview-CO_2, 1999), increased by 1.53 ± 0.1 ppmv/y over the period 1980 to 1989. This corresponds to an annual average rate of change in atmospheric carbon emissions of 3.3 ± 0.2 GtC/y (IPCC, 1995). IPCC (2001) reports a decrease in uncertainty resulting in 3.3 ± 0.1 GtC/y.

The NOAA/CMDL's measurement system includes 35 stations around the world, but complete information for the period 1980–1989 is only available from seven stations: Barrow, Cold Bay, Key Biscayne, Mauna Loa, Niwot Ridge, Samoa, and the South Pole (see Figure 6). Information about this time period, excluding some years, is also possible from eight other stations: Ascension Island, Azores, Cape Kumukahi, Guam, Mould Bay, Palmer Station, Seychelles, and the Virgin Islands.

[4] National Oceanic Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory.

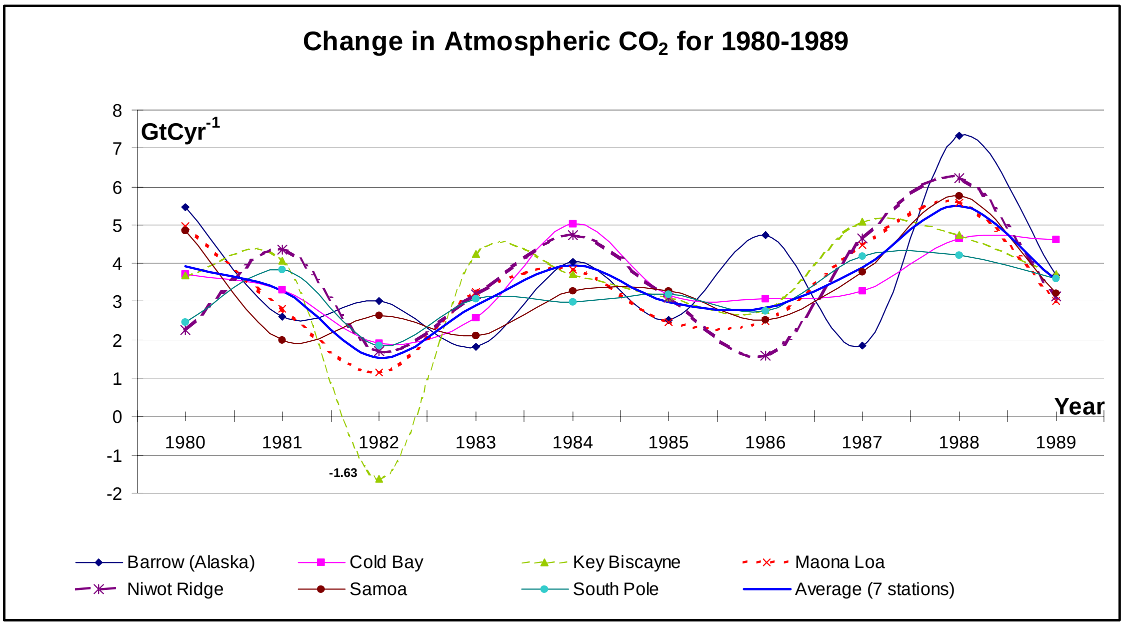

Figure 6: Changes in atmospheric CO_2 (deduced from direct observations from NOAA/CMDL stations) for 1980–1989. Data in ppmv/y were obtained from seven observation stations: Barrow, Cold Bay, Key Biscayne, Mauna Loa, Niwot Ridge, Samoa, and the South Pole, and were then accounted in GtC/y. The solid line represents the average from these seven stations.

The global reservoir changes of carbon in the atmosphere for 1980–1989 were obtained from direct measurements within the NOAA/CMDL framework and measured in ppmv/y and were then calculated in GtC/y as recommended by the IPCC. Figure 6 shows the variability of this data.[5]

As can be seen from Figure 6, the net carbon flux into the atmosphere is quite variable in space and time. This variability is considered in more detail. To this end, frequency distributions in the form of histograms are established, as follows: for a given net atmospheric carbon flux, its minimum–maximum range on the y-axis is identified, which is subdivided into intervals of variable (but equal) width. Subsequently, the time axis is sampled (in equal time steps). The y-values (i.e., net carbon fluxes) to these x-values are used to construct a frequency distribution based on which of the equal-width intervals on the y-axis they fall into. Figures 7–9 show histograms, which combine or refer to the measurements of the seven stations mentioned in Figure 6 for 1980–1989, 1980 and 1989, respectively. In each of the latter two cases, we only evaluated individual points in time, namely 1980 and 1989.

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[5] According to Battle *et al.* (2000), 0.471 ppmv/y converts to 1 GtC/y, that is, 1 ppmv/y converts to 2.123 GtC/y.

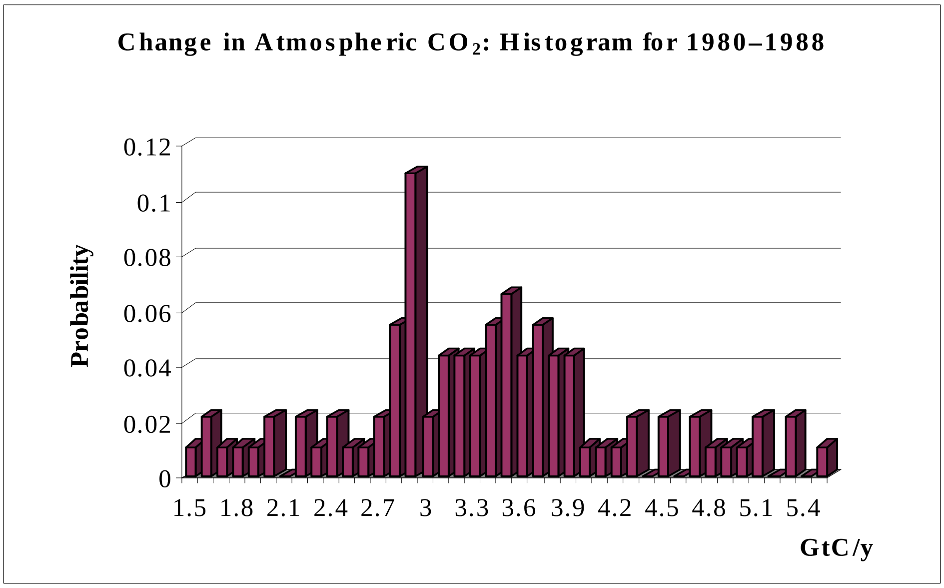

Figure 7: Change in atmospheric CO_2: Histogram for 1980–1988. The data were obtained from the following seven NOAA/CMDL observation stations: Barrow, Cold Bay, Key Biscayne, Mauna Loa, Niwot Ridge, Samoa, and the South Pole. Minimum value: 1.5 GtC/y; maximum value: 5.5 GtC/y; expected value: 3.36 GtC/y; standard deviation: 0.78 GtC/y.

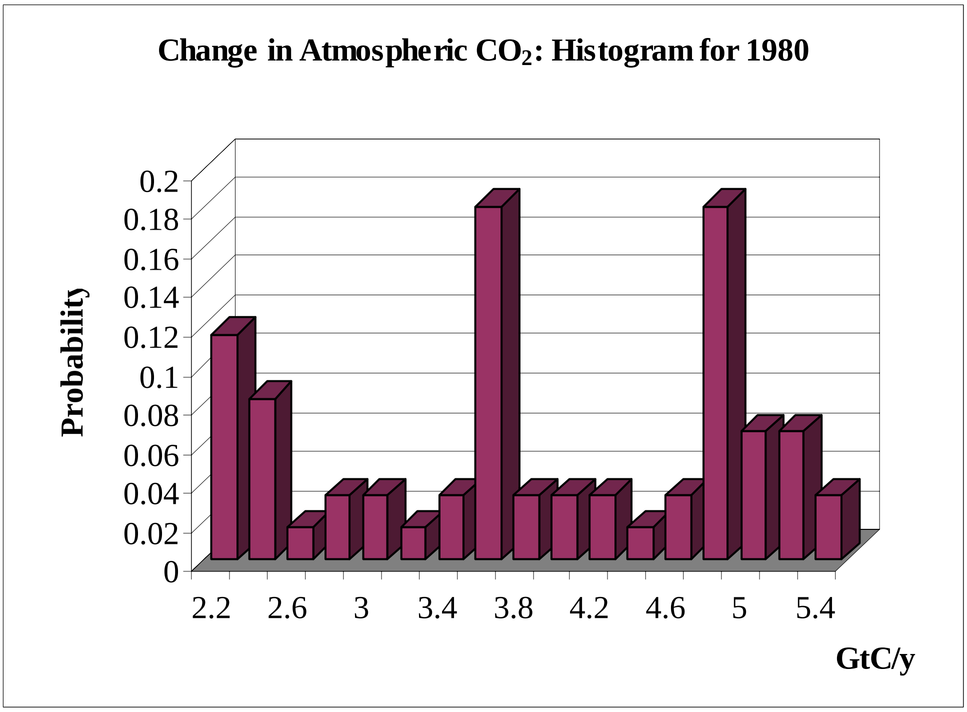

Figure 8: Change in atmospheric CO_2: Histogram for 1980. The data were obtained from the following seven NOAA/CMDL observation stations: Barrow, Cold Bay, Key Biscayne, Mauna Loa, Niwot Ridge, Samoa, and the South Pole. Minimum value: 2.2 GtC/y; maximum value: 5.4 GtC/y; expected value: 3.82 GtC/y; standard deviation: 1.07 GtC/y.

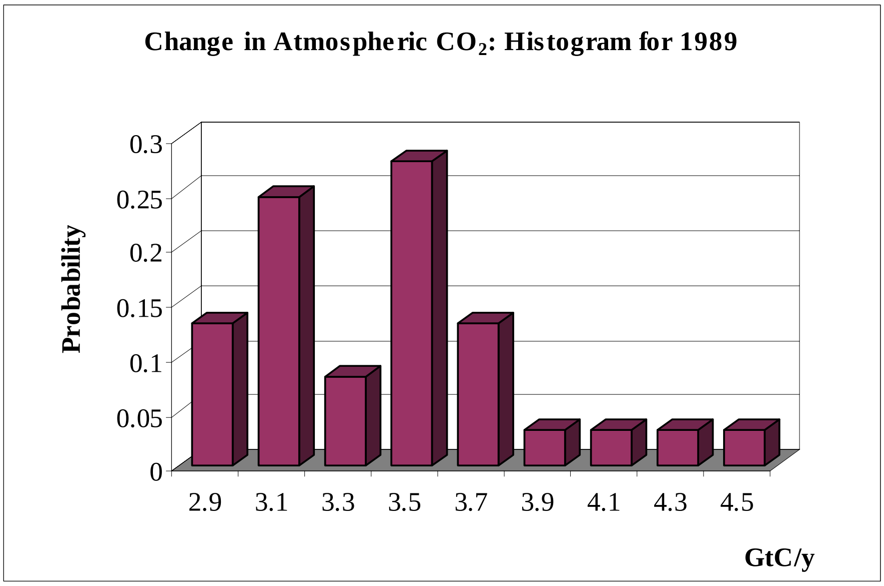

Figure 9: Change in atmospheric CO_2: Histogram for 1989. The data were obtained from the following seven NOAA/CMDL observation stations: Barrow, Cold Bay, Key Biscayne, Mauna Loa, Niwot Ridge, Samoa, and the South Pole. Minimum value: 2.9 GtC/y; maximum value: 4.5 GtC/y; expected value: 3.42 GtC/y; standard deviation: 0.16 GtC/y.

We make use of the statistical data (minimum, maximum, expected value, standard deviation) derived with the help of these histograms for the probabilistic VTC in Section 5, but only for 1980 to 1989 (see Table 2). For 1980 and 1989, the statistical data are mentioned in the figure captions to Figures 8 and 9. For 1981 to 1988 the histograms are not shown. However, all statistical data are summarized in Table 2.

Table 2: Change in atmospheric CO_2: Main statistical characteristics to the histograms for 1980 to 1989 (GtC/y).

Years	Minimum	Maximum	Expected Value	Standard Deviation
1980	2.2	5.4	3.82	1.07
1981	2.0	4.4	3.28	0.26
1982	2.2	3.0	2.98	0.78
1983	2.0	4.2	2.89	0.76
1984	2.9	5.0	3.94	0.45
1985	2.5	3.3	2.97	0.16
1986	2.1	4.7	2.84	0.18
1987	1.9	5.1	3.90	1.05
1988	4.2	5.6	5.50	0.79
1989	2.9	4.5	3.42	0.16

3.3 Global CO_2 Emissions from Fossil Fuel Burning, Cement Manufacture and Gas Flaring

In this Section, we investigate the major component of the carbon budget, the global CO_2 emissions from fossil fuel burning, cement manufacture and gas flaring (simply fossil fuel burning or combustion hereafter).

Emissions of CO_2 from the consumption of fossil fuels have resulted in an increasing concentration of CO_2 in the atmosphere of the earth. Combined with CO_2 releases from changes in land use, these emissions have perturbed the natural cycling of carbon, resulting in the accumulation of CO_2 in the atmosphere, significantly influencing the climate of the earth.

Annual estimates of global emissions from fossil fuel burning have been compiled for the time period from 1751 through 1998 (for the period 1950–1998 see Figure 10). These data have been provided by Marland and Rotty (1984), Rotty and Marland (1986), Marland (1989), and Marland *et al.* (2000).[6] The primary data for these estimates are annual energy statistics compiled by the UN (2000). In addition, the emissions for 1998 and 1999 have been estimated based on the energy statistics compiled by BP (2000). The estimates of CO_2 emissions from cement manufacture are derived from the data of the United States (US) Department of Interior Bureau of Mines. The estimates of CO_2 emissions from gas flaring are derived from UN data, supplemented with data from the US Department of Energy and national estimates provided by Marland *et al*. (1999).

The average total CO_2 emissions from fossil fuels for the 1980s are represented by Marland *et al.* (2000) to amount to 5.44 ± 0.3 GtC/y, after the revision of the earlier estimate of 5.46 ± 0.3 GtC/y (Andres *et al.*, 2000) used in the Special Report on Radiative Forcing (IPCC, 1995) and in IPCC (1996). Emissions rose from 6.1 GtC/y in 1990 to 6.5 GtC/y in 1999. The average value of emissions in the 1990s was 6.3 ± 0.4 GtC/y.

We examined the behavior of the global net CO_2 flux from fossil fuel burning for the time periods 1960–1969, 1970–1979, and 1980–1989, respectively. Figures 11–13 show the respective histograms.

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[6] The global CO_2 emissions from fossil burning, cement manufacture and gas flaring were revised by Marland *et al*. on 9 December 2002. These data exhibit minor modifications beginning with the year 1973 and also include the year 1999.

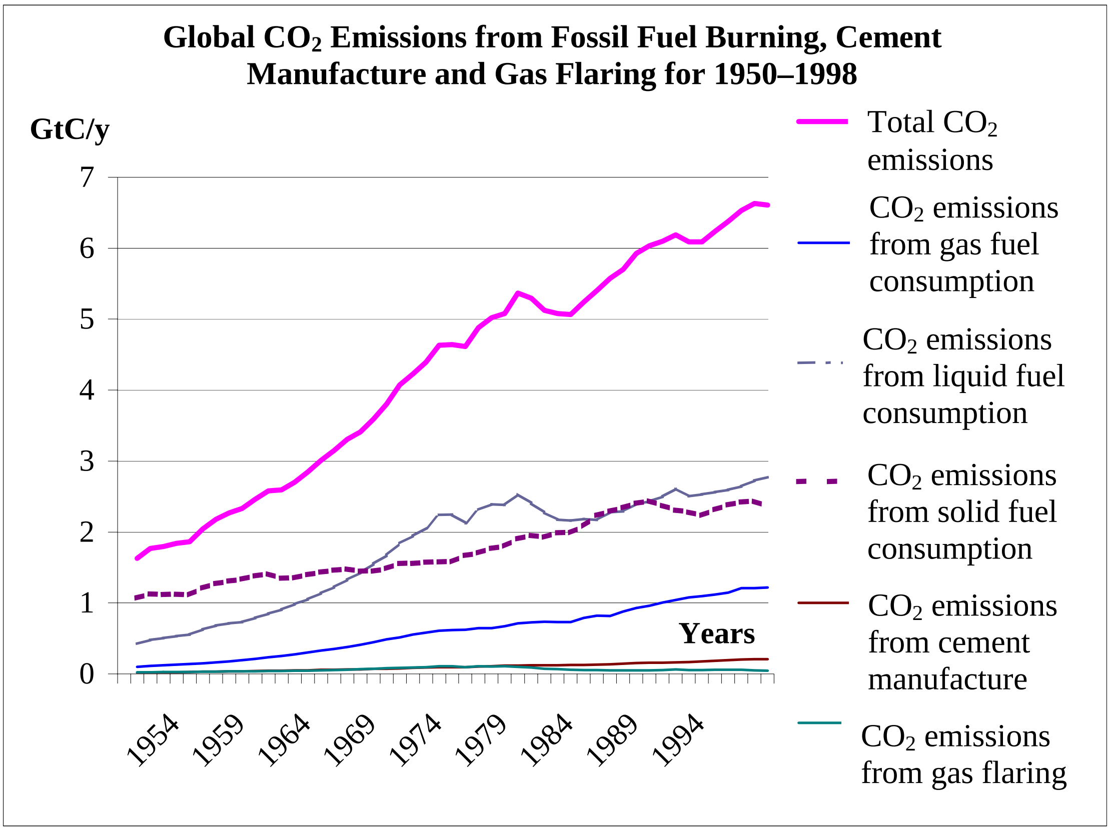

Figure 10: Global CO_2 emissions from fossil fuel burning, cement manufacture and gas flaring for 1950–1998 (in GtC/y). Source: Marland *et al.* (2000).

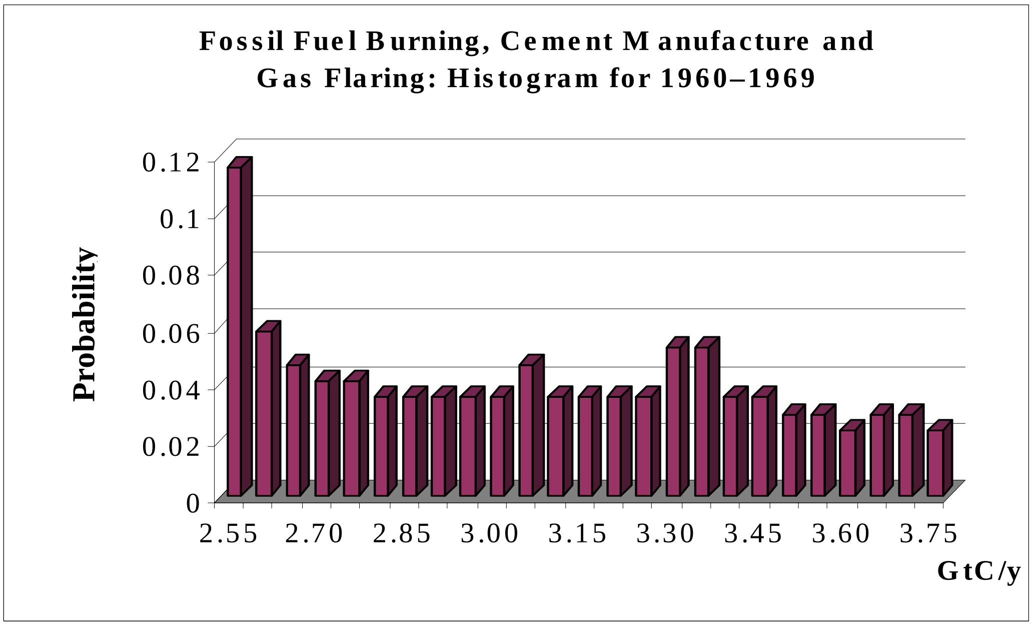

Figure 11: Fossil fuel burning, cement manufacture and gas flaring: Histogram for 1960–1969 (based on data from Marland *et al.*, 2000). Minimum value: 2.55 GtC/y; maximum value: 3.75 GtC/y; expected value: 3.06 GtC/y; standard deviation: 0.14 GtC/y.

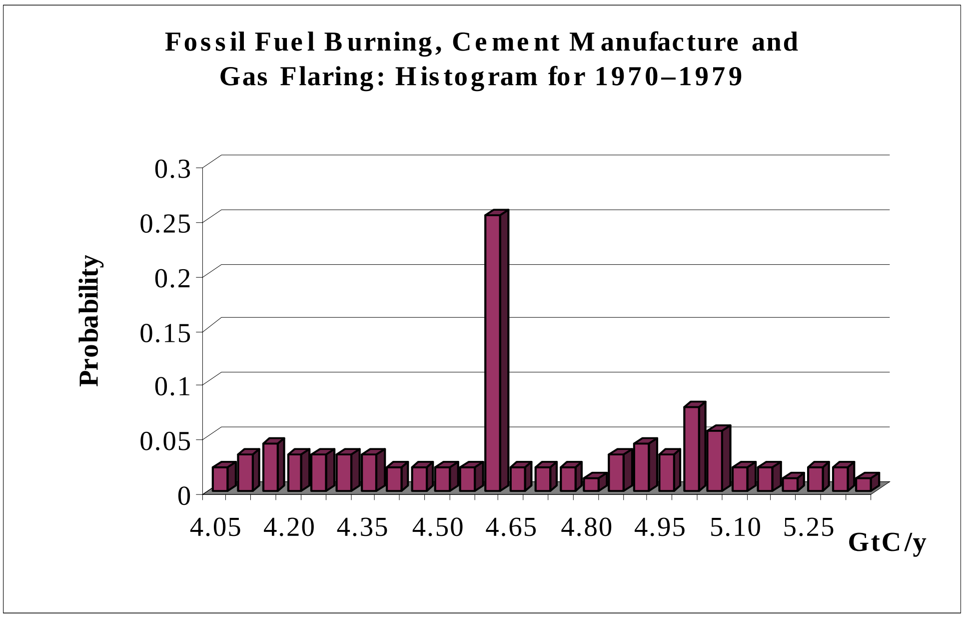

Figure 12: Fossil fuel burning, cement manufacture and gas flaring: Histogram for 1970–1979 (based on data from Marland *et al.*, 2000). Minimum value: 4.05 GtC/y; maximum value: 5.35 GtC/y; expected value: 4.66 GtC/y; standard deviation: 0.11 GtC/y.

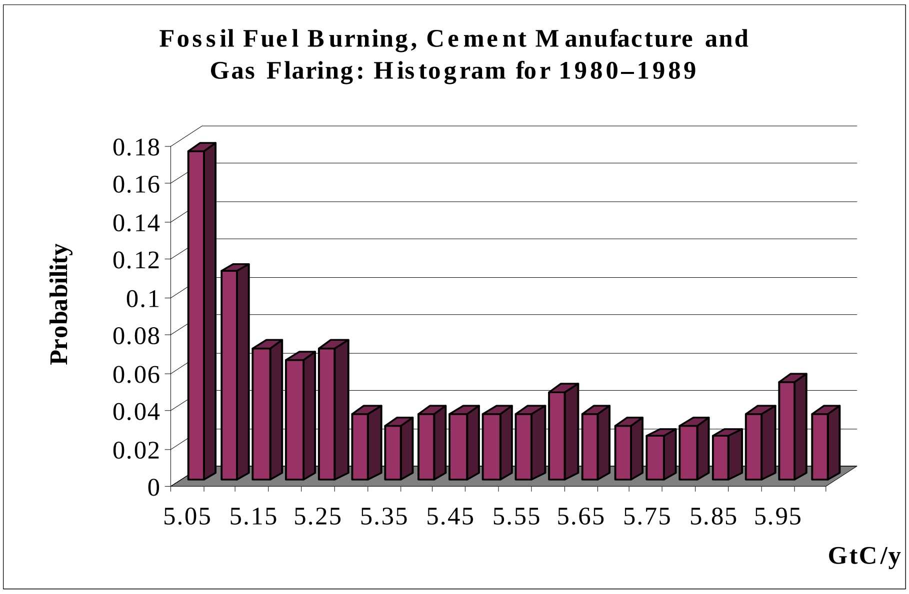

Figure 13: Fossil fuel burning, cement manufacture and gas flaring: Histogram for 1980–1989 (based on data from Marland *et al.*, 2000). Minimum value: 5.05 GtC/y; maximum value: 6.0 GtC/y; expected value: 5.39 GtC/y; standard deviation: 0.1 GtC/y.

We make use of the statistical data (minimum, maximum, expected value, standard deviation) derived with the help of these histograms for 1960–1969, 1970–1979, and 1980–1989 for the probabilistic VTC in Section 5. Table 3 summarizes all statistical data (see also captions to Figures 11–13).

Table 3: Main probabilistic characteristics for distributions of the CO_2 emissions from fossil fuel combustion and cement production for 1960–1969, 1970–1979, and 1980–1989 (GtC/y).

Years	Minimum	Maximum	Expected Value	Standard Deviation
1960–1969	2.55	3.75	3.06	0.14
1970–1979	4.05	5.35	4.66	0.11
1980–1989	5.05	6.0	5.39	0.10

3.4 Conclusions

From the above examples (see Figures 7–9, 11–13), it becomes evident that the uncertainties with respect to the changes in atmospheric CO_2 and the CO_2 emissions from fossil fuel burning may not be normally distributed around their mean values. The characterization of uncertainties by equal-sided (symmetric) intervals leaves valuable information unutilized.

In Section 4, we consider the probabilistic, risk-based approach. As noted in Section 2.5, the description of net carbon fluxes by uncertainty distributions may affect the verification time, which will lead us to consider risk in the VTC.

4 Methodology

In this Section, we present a method for determining the verification time for emission systems that are characterized by uncertainties on the basis of probabilities. This will lead us to Section 5, where we calculate the verification times for several global-scale examples.

4.1 Basic Assumptions

To begin with, we consider the following standard conditions and assumptions:

- We consider two points in time, t_1 and t_2, with $t_1 < t_2$.
- We assume that we know the uncertainty distributions that characterize net carbon emissions at t_1 and t_2.

  Hence, we can consider the two random variables ξ and η at these times. Note that ξ and η may not be statistically independent in reality. Here, we consider the case where they can be treated as statistical independent variables in the context of the VTC for physical reasons (Jonas, 2002).

The random variable ξ can be continuous or discrete, and can thus be characterized by the continuous density function $p_\xi(a)$ or by discrete probable values a_i, $i=\overline{1,n}$, and their corresponding probabilities p_i, $i=\overline{1,n}$:

a_i	a_0	a_1	$\cdots$	a_n
p_i	p_0	p_1	$\cdots$	p_n

Similarly for the random variable η:

b_j	b_0	b_1	$\cdots$	b_m
r_j	r_0	r_1	$\cdots$	r_m

- We consider all probable linear curves $F_{net}=F_{net}(\xi,\eta)$, which connect the two points (t_1,ξ) and (t_2,η). We assume that this (first-order) approximation of linear trends is applicable (see Figure 14).
- The uncertainty intervals are given by:

  $$\varepsilon_1(t)=F^+(t)-F_{net}(t), \tag{4.1a}$$

  $$\varepsilon_2(t)=F_{net}(t)-F^-(t), \tag{4.1b}$$

  where $F^+(t)$ and $F^-(t)$ represent the linear boundary conditions for all probable linear curves for time $[t_1,t_2]$.
- We consider the time $\Delta t=t_*-t_1$, where $t_*=t_*(\xi,\eta)$ (see Figure 14). We define the verification time for the GHG emission system, i.e., its (net) emission signal in light of its underlying uncertainty, as follows:

  If the absolute change in net emissions, $F_{net}=F_{net}(\xi,\eta)$ between t_* and t_1, $(t_1<t_*)$ becomes greater than the uncertainty $\varepsilon_2(t)$ at time t_*, i.e.,

  $$\Delta F_{net}(t_*)\ge\varepsilon_2(t_*), \tag{4.2}$$

  the time $\Delta t=t_*-t_1$ is called the verification time of F_{net}.

  It is noted that Δt is a random variable because $\Delta t=\Delta t(\xi,\eta)=t_*(\xi,\eta)-t_1$. Thus, Δt can be described by the following table:

$\Delta t_{a_i,b_j}$	$\Delta t_{a_0b_0}$	$\Delta t_{a_1b_0}$	$\cdots$	$\Delta t_{a_nb_m}$
$g_{i,j}$	p_0r_0	p_1r_0	$\cdots$	p_nr_m

Under these conditions and assumptions, we can continue with describing the methodology to assess the probabilistic or risk-based verification time.

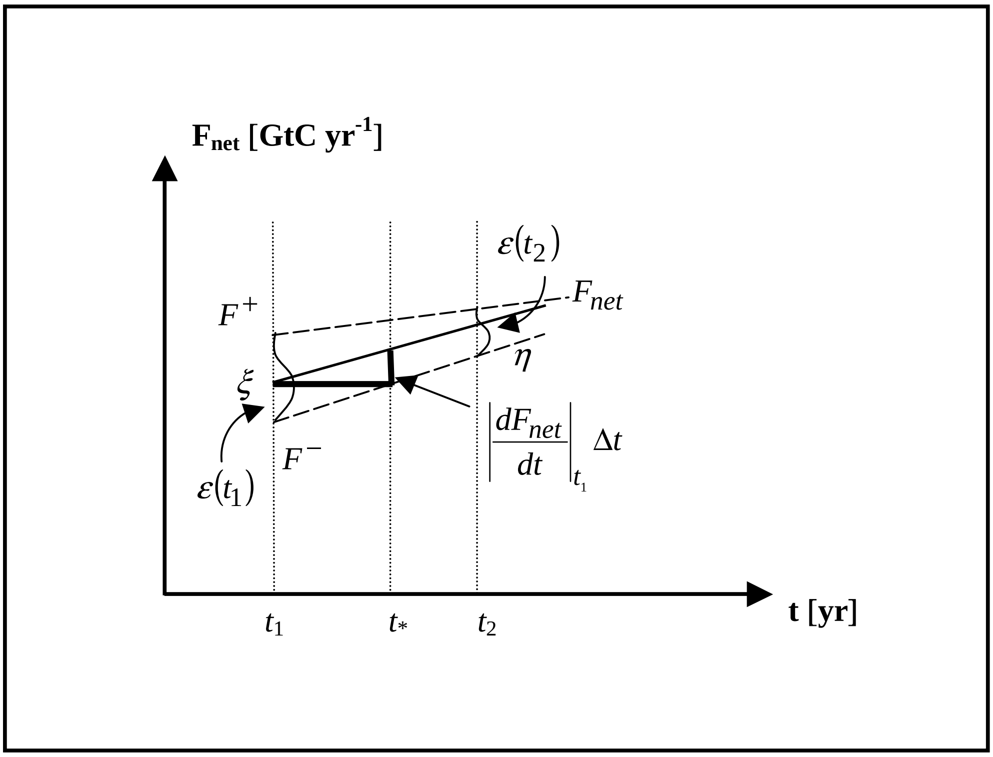

Figure 14: Probable verification: Simplified linear graphical representation of Equation (4.2).

4.2 Risk Based VTC

We consider probabilistic verification under the conditions described in the previous Section. Under the non-restrictive assumption that first-order (linear) approximations are applicable, we can rewrite Equation (4.2):

$$\left|\frac{dF_{net}}{dt}\right|_{t_1} \Delta t \geq \varepsilon_2(t_*) \,. \tag{4.3}$$

The linear function $F^- = F^-(t)$, which connects the two points (t_1, a_0) and (t_2, b_0) is given by:

$$F^- = \frac{b_0 - a_0}{t_2 - t_1} t + \frac{a_0 t_2 - b_0 t_1}{t_2 - t_1} \,. \tag{4.4a}$$

Similarly, the equation for $F^+ = F^+(t)$ (but not needed below) is given by:

$$F^+ = \frac{b_m - a_n}{t_2 - t_1} t + \frac{a_n t_2 - b_m t_1}{t_2 - t_1} \,. \tag{4.4b}$$

We consider the emission level at t_1, ξ, for $t \geq t_1$, i.e.,

$$F = F(t) = \xi \,. \tag{4.5}$$

According to Figure 14, (t_*, ξ) represents the point, where the two lines $F^-(t)$ [Equation (4.4a)] and $F(t) = \xi$ [Equation (4.5)] intersect. It is given by:

$$t_* = \xi \frac{t_2 - t_1}{b_0 - a_0} - \frac{a_0 t_2 - b_0 t_1}{b_0 - a_0} \,. \tag{4.6}$$

Therefore:

$$\Delta t = t_* - t_1 = \xi \frac{t_2 - t_1}{b_0 - a_0} - \frac{a_0 t_2 - b_0 t_1}{b_0 - a_0} - t_1 = (\xi - a_0) \frac{t_2 - t_1}{b_0 - a_0} \,. \tag{4.7}$$

As a result, we obtain the random quantity $\Delta t = \Delta t(\xi) = t_*(\xi) - t_1$. We now compute the minimal $\Delta\tilde{t}$ for which:

$$P(\Delta\tilde{t} \geq \Delta t) = 0.95 \,, \tag{4.8}$$

or, equivalently:

$$P(\Delta\tilde{t} < \Delta t) = 0.05 \,. \tag{4.9}$$

According to Equation (4.8), it is required that the probability of $\Delta\tilde{t}$ taking on a value $\geq \Delta t$ is 0.95. We can rewrite Equation (4.8) with the help of Equation (4.7):

$$P\left(\Delta\tilde{t} \geq (\xi - a_0) \frac{t_2 - t_1}{b_0 - a_0} \right) = 0.95 \,. \tag{4.10}$$

Setting $u = \dfrac{t_2 - t_1}{b_0 - a_0}$ (> 0 without restricting generality):

$$P\left(\Delta\tilde{t} \geq (\xi - a_0) u \right) = 0.95 \,, \tag{4.11}$$

or equivalently:

$$P\left(\xi \leq a_0 + \frac{\Delta\tilde{t}}{u} \right) = 0.95 \,. \tag{4.12}$$

We can thus also consider z_{95} such that

$$P(\xi \le z_{95}) = 0.95 . \quad (4.13)$$

Setting $a_0 + \frac{\Delta \tilde{t}}{u} = z_{95}$:

$$\Delta \tilde{t} = (z_{95} - a_0)u = z_{95}\frac{t_2 - t_1}{b_0 - a_0} - \frac{a_0 t_2 - b_0 t_1}{b_0 - a_0} - t_1 . \quad (4.14)$$

In Section 5, we apply the probabilistic VTC to carbon accounting on the global scale. To these ends, we will make use of the examples treated in Section 3. We are interested in the verification times involved and how they change depending on changes in our knowledge of the underlying uncertainties. Possible generalizations of our methodology are discussed in Section 6.

5 Applications

In this Section, we apply the risk-based VTC on the global scale. To illustrate the calculation procedure and how our results compare with those of the deterministic approach, we first consider three examples: one referring to the change in atmospheric CO_2 for 1980–1989 and the other two examples referring to the global CO_2 emissions from fossil fuel burning for 1965–1985 and 1965–1975, respectively. We use the data presented in Section 3.

5.1 Three Examples

In the first example, we consider the change in atmospheric CO_2 for the time period 1980–1989. According to the data represented in Figures 8 and 9 and with the help of Equation (4.10) from Section 4, we obtain:

- t_1 = 1 Jan. 00GMT, 1980:

  Value ranges [2.2–5.4] GtC/y or $\varepsilon_1(t_1) + \varepsilon_2(t_2) = 3.20$ GtC/y; and

- t_2 = 1 Jan. 00GMT, 1990:

  Value ranges [2.9–4.5] GtC/y or $\varepsilon_1(t_1) + \varepsilon_2(t_2) = 1.60$ GtC/y.

With the help of this information in combination with Equation (4.10), we find that the VT exceeds 2.9 years with approximately 80% probability and does not exceed 40 years with approximately 90% probability. The median VT is about 20 years (see Figure 15).

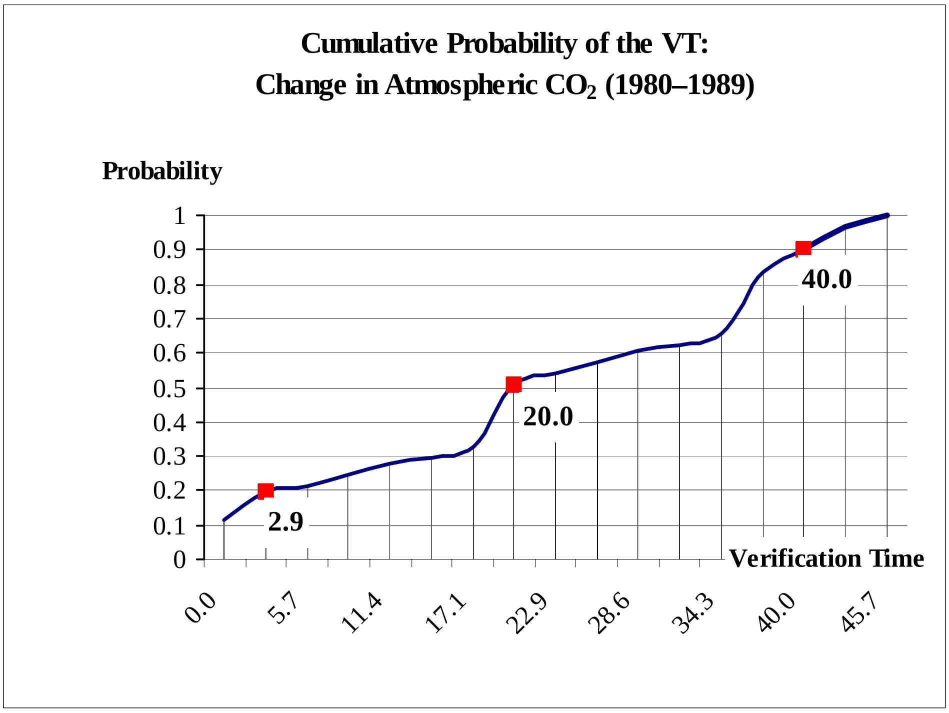

Figure 15: Cumulative probability of the VT: Change in atmospheric CO_2 for 1980–1989 [graphical representation of Equation (4.10)]. For this period, the VT exceeds 2.9 years with approximately 80% probability and does not exceed 40 years with approximately 90% probability. The median VT is about 20 years.

In the second example, we consider global CO_2 emissions from fossil fuel burning for the time period 1965–1985. Here, we obtain:

- t_1 = 1 Jan. 00GMT, 1965, as the mean over the period 1960 to 1969:

  Value ranges [2.55–3.75] GtC/y or $\varepsilon_1(t_1)+\varepsilon_2(t_2)=1.20$ GtC/y; and

- t_2 = 1 Jan. 00GMT, 1985, as the mean over the period 1980 to 1989:

  Value ranges [5.05–6.00] GtC/y or $\varepsilon_1(t_1)+\varepsilon_2(t_2)=0.95$ GtC/y.

With the help of this information in combination with Equation (4.10), we find that the VT exceeds 0.6 years with approximately 80% probability and does not exceed 8.0 years with approximately 90% probability. The median VT is about 3.8 years (see Figure 16).

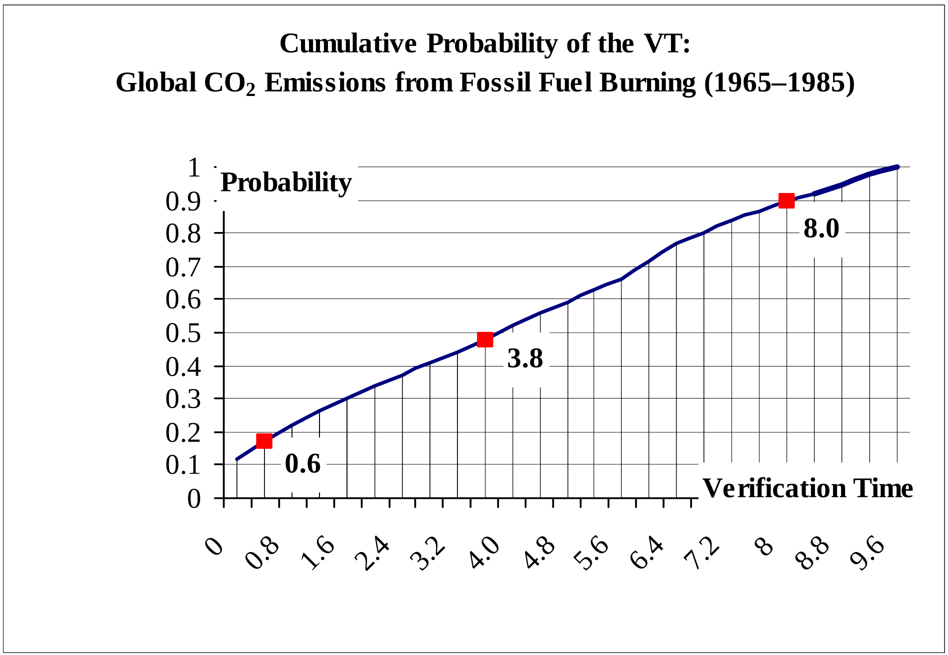

Figure 16: Cumulative probability distribution of the VT: Global CO_2 emissions from fossil fuel burning for 1965–1985 [graphical representation of Equation (4.10)]. For this period, the VT exceeds 0.6 years with approximately 80% probability and does not exceed 8.0 years with approximately 90% probability. The median VT is about 3.8 years.

In the third example, we again consider global CO_2 emissions from fossil fuel burning, but for the time period 1965–1975. Here, we obtain:

- t_1 = 1 Jan. 00GMT, 1965, as the mean over the period 1960 to 1969:

  Value ranges [2.55–3.75] GtC/y or $\varepsilon_1(t_1)+\varepsilon_2(t_2)=1.20$ GtC/y; and

- t_2 = 1 Jan. 00GMT, 1975, as the mean over the period 1970 to 1979:

  Value ranges [4.05–5.35] GtC/y or $\varepsilon_1(t_1)+\varepsilon_2(t_2)=1.30$ GtC/y**.**

With the help of this information in combination with Equation (4.10), we find that the VT exceeds 0.5 years with approximately 80% probability and does not exceed 6.7 years with approximately 90% probability. The median VT is about 3.2 years (see Figure 17).

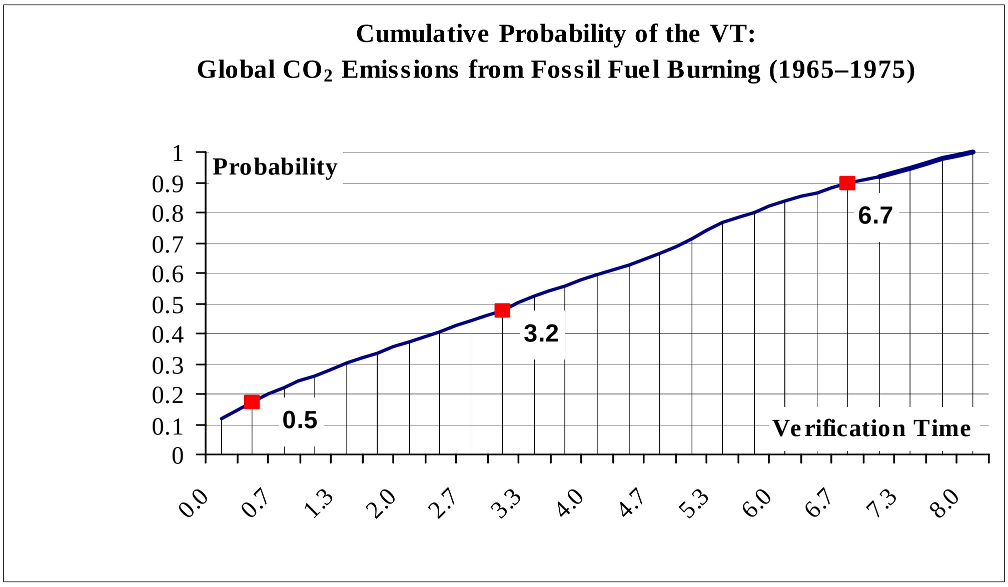

Figure 17: Cumulative probability of the VT: Global CO_2 emissions from fossil fuel burning for 1965–1975 [graphical representation of Equation (4.10)]. For this period, the VT exceeds 0.5 years with approximately 80% probability and does not exceed 6.7 years with approximately 90% probability. The median VT is about 3.2 years.

5.2 Comparison with the Deterministic Case

We now consider the same examples as in Section 5.1, but for the deterministic case, also under the assumption that first-order approximations (linear trends) are applicable (see also Jonas *et al.*, 1999b). In the first example, we examine the change in atmospheric CO_2 for 1980–1989. We make use of the NOAA data for 1980 and 1989, which are shown in Figures 8 and 9. The same data were used in Sections 3.2 and 5.1.

With the help of these sources, and the ability to describe uncertainties of changes in atmospheric CO_2 by ±6% (IPCC, 1995; see also Section 3.2), we can specify:

- t_1 = 1 Jan. 00GMT, 1980:

  $F_{atm}(t_1) = mean = 3.82$ GtC/y (see Figure 8);

  $\varepsilon(t_1) = (3.82 \cdot 6/100) \cdot 2 \approx 0.23 \cdot 2 = 0.46$ GtC/y;

- t_2 = 1 Jan. 00GMT, 1990:

  $F_{atm}(t_2) = mean = 3.42$ GtC/y (see Figure 9);

  $\varepsilon(t_2) = (3.42 \cdot 6/100) \cdot 2 \approx 0.21 \cdot 2 = 0.42$ GtC/y;

- $\left|\dfrac{dF_{atm}}{dt}\right|_{t_1} \approx 0.04 \dfrac{GtC\,yr^{-1}}{yr}$.

The verification time can be calculated with the help of Equation (2.3). According to this equation we calculate for the verification time $\Delta t \approx 5.5\, y$, which is much less compared with the probabilistic case (its median VT is about 20 years).

The difference between the median VTs (20 years) and the deterministic VT (5.5 years) in this example is considerable and requires further discussion:

1. The consideration of changes in atmospheric CO_2 at two specific times (here, 1980 and 1989) may not be sufficient to correctly grasp their dynamics in between these two times (i.e., for 1980–1989). This is the case here, as can also be inferred from Figure 18. The 1980 and 1989 changes in atmospheric CO_2 suggest a decreasing trend of -0.04 GtC yr^{-1}/yr, while a linear regression for 1980–1989 results in an increasing trend of about +0.04 GtC yr^{-1}/yr (Jonas *et al.*, 1999b: Section 4.1). This raises the issue of appropriately selecting representative time intervals for the calculation of VTs.

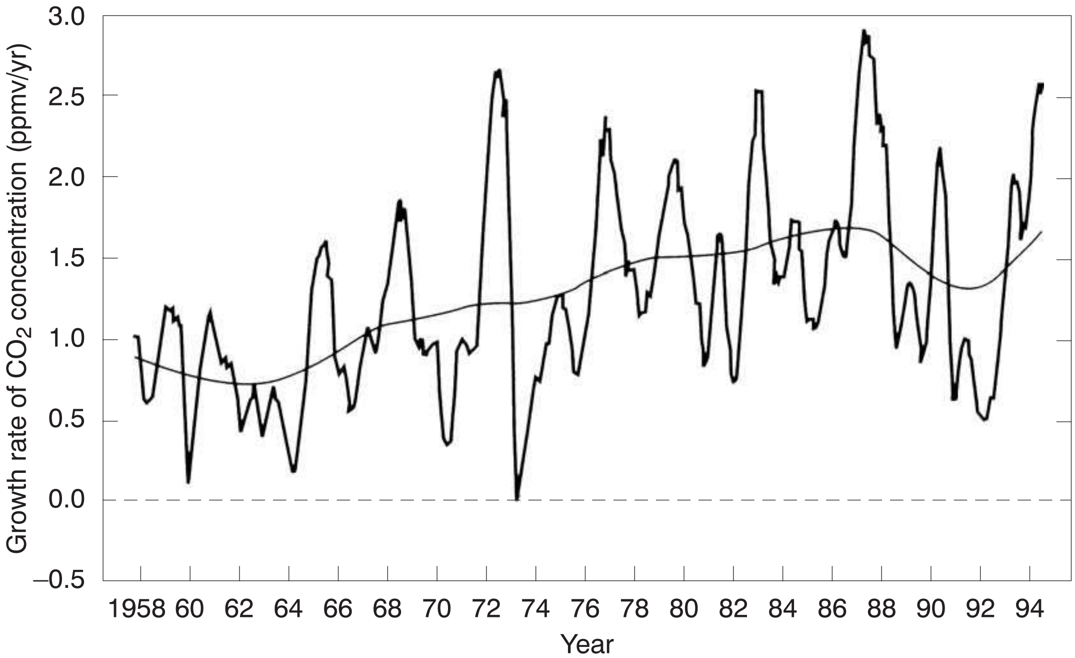

Figure 18: Growth rate of CO_2 concentrations since 1958 in ppmv/yr^{-1} at the Mouna Loa, Hawaii station. Of importance in the context here are the high growth rates of the late 1980s, the low growth rates of the early 1990s, and the following upturn in the growth rate. The smoothed curve shows the same data but filtered to suppress variations on time scales less than approximately 10 years. Source: Schimel *et al.* (1996: Figure 2.2).

2. The two-points-in-time (1980 and 1989) trend (-0.04 GtC yr^{-1}/yr) as well as the decade (1980–1989) trend of changes in atmospheric CO_2 (+0.04 GtC yr^{-1}/yr) are small. For comparison, the 1965–1985 and 1965–1975 trends of emissions from fossil fuel burning, cement manufacture and gas flaring (0.12 and 0.16 GtC yr^{-1}/yr, respectively; see second and third example below) are greater by almost a factor of four. Inequality (2.3) tells us that a great amount of uncertainty in the net emissions (numerator) and/or

— of relevance here — a relatively small rate of net emission change (denominator) may cause the VT to become very great. Therefore, a small deviation from the given rate of net emission change may entail a considerable deviation from the (deterministic) VT.

In the second example, we consider global CO_2 emissions from fossil fuel burning for 1965–1985. We make use of the data reported by the Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory (Marland *et al.*, 1999), which are shown in Figure 10. The same data were used in Sections 3.3 and 5.1.

With the help of the sources and the ability to describe uncertainties of CO_2 emissions from fossil fuel burning by ±10% (Gusti and Jęda, 2002), we can specify:

- t_1 = 1 Jan. 00GMT, 1965, as the mean over the period 1960 to 1969:

  $F_{FF}(t_1) = mean$ = 3.06 GtC/y (see Figure 11);

  $\varepsilon(t_1) = (3.06 \cdot 10/100) \cdot 2 \approx 0.3 \cdot 2 = 0.6$ GtC/y;

- t_2 = 1 Jan. 00GMT, 1985, as the mean over the period 1980 to 1989:

  $F_{FF}(t_2) = mean$ = 5.39 GtC/y (see Figure 13);

  $\varepsilon(t_2) = (5.39 \cdot 10/100) \cdot 2 \approx 0.5 \cdot 2 = 1.1$ GtC/y;

- $$\left|\frac{dF_{FF}}{dt}\right|_{t_1} \approx 0.12 \;\frac{GtC\, yr^{-1}}{yr}\;.$$

Making use of Equation (2.3), we find the verification time to be $\Delta t \approx 2.7y$, which is more optimistic compared with the probabilistic case (its median VT is about 3.8 years).

In the third example, we consider global CO_2 emissions from fossil fuel burning for 1965–1975. Following the second example, we can specify:

- t_1 = 1 Jan. 00GMT, 1965, as the mean over the period 1960 to 1969:

  $F_{FF}(t_1) = mean$ = 3.06 GtC/y (see Figure 11);

  $\varepsilon(t_1) = (3.06 \cdot 10/100) \cdot 2 \approx 0.3 \cdot 2 = 0.6$ GtC/y;

- t_2 = 1 Jan. 00GMT, 1975, as the mean over the period 1970 to 1979:

  $F_{FF}(t_2) = mean$ = 4.66 GtC/y (see Figure 13);

  $\varepsilon(t_2) = (4.66 \cdot 10/100) \cdot 2 \approx 0.47 \cdot 2 = 0.9$ GtC/y;

- $$\left|\frac{dF_{FF}}{dt}\right|_{t_1} \approx 0.16 \;\frac{GtC\, yr^{-1}}{yr}\;.$$

According to Equation (2.3), we find the verification time to be $\Delta t \approx 2.1y$, which is again more optimistic compared with the probabilistic case (its median VT is about 3.2 years).

6 Concluding Remarks

This study acknowledges the fact that the Kyoto Protocol is in need of a solid and robust VTC. Here, we study a new, probabilistic, VTC vis-à-vis the deterministic VTC that has been investigated by Jonas *et al.* (1999b) and Gusti and Jęda (2002). The objectives of the study are:

- to study the conditions of using a probabilistic VTC approach,
- to develop a methodology for setting the VTC on a probabilistic basis, and
- to apply the probabilistically-based VTC and to analyze its strengths and weaknesses.

According to these objectives, we investigated the uncertainties of global net carbon fluxes, here the change in atmospheric CO_2 and the CO_2 emissions from fossil fuel burning, cement manufacture and gas flaring. For a number of reasons, namely:

- data availability,
- consistency in accounting net carbon fluxes, and
- spatio-temporal conditions, which correspond to the current level of sophistication that is realized in the approach,

investigations are carried out on the global scale. The key idea underlying these calculations is that temporal verification conditions on sub-global scales are simulated.

Two conclusions emerge from the study: (1) characterizing changes in global net carbon emissions by equal-sided (symmetric) uncertainties, as practised by the IPCC, may not necessarily be appropriate and leaves valuable information unutilized; and (2) the comparison of probabilistically and deterministically determined VTs shows that they differ — the probabilistic VT tends to be greater (more conservative) compared with the deterministic VT.

With respect to the issue of verifying net emission fluxes under the Kyoto Protocol, it becomes clear that more attention needs to be given to the evaluation and advancement of risk-based approaches. To these ends, it is important to characterize net carbon fluxes stochastically also in terms of their dynamics, i.e., to go beyond the concept of constant slopes. Also, our approach is restricted to two points in time, for which we have all available information. However, practice shows that information is (for example) also available prior to this time interval — information, which, in turn, may influence the subsequent evolvement of the signal. Therefore, future investigations should also consider cases with available information at more than two points in time.

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